The investigation of the high frequency hopping conductivity in two- and three-dimensional electron gas by an acoustic method.

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Abstract

High-frequency (HF) conductivity (σ_{hf}) measured by an acoustical method has been studied in GaAs/AlGaAs heterostructures in a linear and nonlinear regime on acoustic power. It has been shown that in the quantum Hall regime at magnetic fields corresponding to the middle of the Hall plateaus the HF conductivity is determined by the sum of the conductivity of 2-dimensional electrons in the high-mobility channel and the hopping conductivity of the electrons in the doped thick AlGaAs layer. The dependence of these conductivities on a temperature is analyzed. The width of the Landau level broadened by the impurity random potential is determined.

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I. INTRODUCTION

If one places a semiconducting heterostructure over a piezoelectric platelet along which acoustic surface wave (SAW) is being propagated, the SAW undergoes additional attenuation associated with the interaction of the electrons of heterostructure with the electric field of SAW. This is the basis of the acoustic method pioneered by Wixforth [1] for the investigation of GaAs/AlGaAs heterostructures. In contrast to [1] in the present work it has been found that in a GaAs/AlGaAs heterostructure ($\mu = 1.28 \cdot 10^5 cm/Vs$, $n = 6.7 \cdot 10^{11} cm^{-2}$) in the quantum Hall regime the conductivities σ_{hf} measured by an acoustic method do not coincide with σ_{dc} obtained from the direct-current measurements: $\sigma_{dc} = 0$, whereas σ_{hf} has a finite value depending on a temperature, magnetic field and SAW intensity. And this is the main objective of the present work to elucidate the nature of this HF conductivity.

The theoretical absorption coefficient can be presented in the following way [2]:

$$\Gamma = 8.68 \frac{K^2}{2} kA \frac{(4\pi\sigma_{xx}/\epsilon_s v)c(k)}{1 + [(4\pi\sigma_{xx}/\epsilon_s v)c(k)]^2}, A = 8b(k)(\epsilon_1 + \epsilon_0)\epsilon_0^2 \epsilon_s exp(-2ka), \qquad (1)$$

where K^2 is the electromechanical coupling coefficient of piezoelectric substrate, k and v are the SAW wavevector and the velocity respectively, a is the vacuum gap width between the lithium niobate platelet and the sample, σ_{xx} is the dissipative HF conductivity of 2DEG, ϵ_1, ϵ_0 and ϵ_s are the dielectric constants of lithium niobate, vacuum and semiconductor respectively; b and c are some complex functions of a, k, ϵ_1, ϵ_0 and ϵ_s. When $(4\pi\sigma_{xx}/\epsilon_s v)c(k) = 1$, Γ achieves the maximum Γ_m. In the case when $\sigma_{xx}/v << 1$ (quantum Hall regime) $\Gamma \propto \sigma_{xx}$. Thus, the SAW electronic attenuation may be taken as a measure of the heterostructure conductivity.

The measurements were carried out in a temperature range 1.5-4.2K , and magnetic fields B up to 7T, with an acoustic frequency in the range of 30-150 MHz. Two kinds of measurements were performed: for the first kind the acoustic power maintained low enough to provide the linearity of results, for the second kind a nonlinear behavior on acoustic power P level was studied intensively at 1.5K.

II. EXPERIMENTAL RESULTS AND DISCUSSION

Fig.1 illustrates the experimental dependences of Γ on B. As long as the SAW attenuation factor is determined by the sample conductivity, quantizing of the electron spectrum in a magnetic field, leading to the SdH oscillations should result in similar peculiarities of the curves of Fig 1. In the present work the experimental data for the magnetic fields corresponding to the quantum Hall regime will be analyzed.

Fig.2 presents the $\Gamma/\Gamma_m(T)$ dependences (f=30 MHz) at magnetic fields 4.8, 3.6, and 2.9T corresponding to the attenuation minima (or the middle of the Hall plateau), which are deduced from the curves of Fig.1, measured at different T and f. As one can see from the figure, as T grows, in a certain temperature range Γ does not depend on a temperature, but at higher temperature begins to grow exponentially, the stronger B, the higher T at which the growth starts.

Such a dependence could not be explained, if one supposes that $\Gamma(T)$ is determined solely by the 2-dimensional electrons. Indeed, in the quantum Hall regime when the Fermi level is

in the middle between two Landau levels, in the temperature range 1.5-4.2 K the temperature dependence of the 2-dimensional conductivity σ_2 (and corresponding attenuation Γ_2) is governed by the activation of electrons from the bound states at the Fermi level to the upper Landau band, i.e. $\Gamma_2 \propto \sigma_2 \propto exp(-\Delta E_g/kT)$.

The dependence of Γ on temperature could be explained, if one supposes that at these levels of B the attenuation adds up both from the SAW attenuation Γ_2 by the 2-dimensional electrons, and Γ_h, due to the electrons, localized on the impurities in the quasi-3-dimensional AlGaAs layer, which supplies carriers to the 2-dimensional channel.

According to [3–5] in a transverse magnetic field $\Gamma_h \propto \sigma_h \propto \omega B^{-2}$ and does not depend on a temperature. Thus the independence of Γ on a temperature at low T could be interpreted as a dominance of the conductivity of the quasi-3-dimensional layer. As T rises the 2-dimensional conductivity becomes prevailing. Based on the above arguments, Γ_2 has been determined as a difference between the experimentally obtained values of Γ and Γ_h. Γ_h is equal to the Γ in the temperature range where Γ is temperature-independent at the magnetic fields 4.8 and 3.6T ($\Gamma_2 << \Gamma_h$). At $B=2.9$T, when there is no temperature flattening , Γ_h was obtained, using the assumption that $\Gamma_h \propto 1/B^2$, [5]. From the plotted dependence $\lg \Gamma_2(1/T)$ the activation energy ΔE_g has been found at $B=$ 4.8, 3.6, 2.9 T. Fig.3 shows the ΔE_g dependence on B. The activation energy obtained from the curves at different magnetic fields appeared to be less than the corresponding energy $\hbar\omega_c/2$. This may be due to the Landau level broadening A caused by the random fluctuation potential.

Supposing $\Delta E_g = \hbar\omega_c/2 - A/2$, where $\hbar$ is the Plank constant, $\omega_c = eB/m^*c$ is the cyclotron frequency, from the ordinate cut-off point of the $\Delta E_g(B) = 0$ curve for $B=2.1$T one could obtain A, which appeared to be 3.4 meV. The slope of the $\Delta E_g(B)$ line in fig.3 appeared to be 0.72 $1/B$, which by 10% differs from the value $e/m^*c=0.8$ $1/B$, if $m^* = 0.07m_0$ for GaAs (m_0 - free electron mass).

The dependence of Γ/Γ_m on P at the same magnetic field is shown in fig.4. It can be seen from the figure, that Γ increases with the increase of P. Keeping in mind that at given magnetic fields Γ_2 is determined by the electron activation to the upper Landau band from the Fermi level, one could suppose that Frenkel-Pool effect i.e the activation energy decrease in electric field E of a SAW [6] is operative in this case.

$$\Gamma_2 \propto \sigma_2 \propto n(T, E) = n_0 exp(2e^{3/2}E^{1/2}\epsilon_s^{-1/2}/kT), \qquad (2)$$

where n_0 -carrier density in the upper Landau level at a linear approach at 1.5K. $Ln\Gamma_2$ plotted against $E^{1/2}$, where $\Gamma_2 = \Gamma - \Gamma_h$, and E is the electric field of SAW [7], which can be presented by a straight line, confirms our model.

III. CONCLUSION

High-frequency conductivity σ_{hf} of a GaAs/AlGaAs heterostructure with a moderate mobility has been studied in the quantum Hall regime ($\sigma_{dc} = 0$) by an acoustic contactless method. It has been shown that up to T=2K σ_{hf} is determined by the hopping conductivity in thick, quasi three-dimensional layers of AlGaAs well described by a Pollak-Geballe model [3]. The two-dimensional HF conductivity in the quantum Hall regime is governed by the electron activation into the upper Landau band. The small value of this conductivity allows one to suppose it also to be of a hopping nature, but this point needs further arguments to be proved.

REFERENCES

[1] A. Wixforth, J.Scriba, M.Wassermeier, J.P.Kotthaus, G.Weinmann and W.Schlapp, Phys.Rev.B**40**, 7874 (1989).

[2] V.D.Kagan, FTP**31**, 470 (1997).

[3] M. Pollak, T. H. Geballe, Phys.Rev.**122**, 1742 (1961).

[4] A.L. Efros, B.I. Shklovskii. Mod. Probl. Conden. Mat. Sci.**10**, Ed. A.L. Efros, M. Pollak, North Holland.

[5] Yu.M.Gal'perin, I.L.Drichko, L.B.Litvak-Gorskaya, FTT**28**, 3374 (1986).

[6] L.S.Stil'bans, Physika Poluprovodnikov, Sovietskoe Radio, Moskva 1967.

[7] I.L.Drichko, A.M.Diakonov, A.M.Kreshchuk, T.A.Polyanskaya, I.G.Savel'ev, I.Yu.Smirnov, A.V.Suslov, to be published in FTP**31**, N11 (1997).

FIGURES

FIG. 1. The experimental dependence of absorption coefficient Γ on B at $f = 30MHz$ at $T = 4.2K$.

FIG. 2. The dependences of Γ/Γ_m ($f = 30MHz$) on T at magnetic fields: 1-4.8T, 2-3.6T, 3-2.9T.

FIG. 3. The dependences of Δ on magnetic field for two frequencies: 1-30MHz, 2-150MHz.

FIG. 4. The dependences of Γ/Γ_m on the RF-generator output power in magnetic fields: 1-4.8T, 2-3.6T, 3-2.9T.